

Low-ionization structures in planetary nebulae

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Abstract. We present new results of a program aimed at studying the physical properties, origin and evolution of those phenomena which go under the somewhat generic definition of “low-ionization, small-scale structures in PNe”. We have obtained morphological and kinematical data for 10 PNe, finding low-ionization structures with very different properties relative to each other, in terms of expansion velocities, shapes, sizes and locations relatively to the main nebular components. It is clear that several physical processes have to be considered in order to account for the formation and evolution of the different structures observed. We present here some results that are illustrative of our work – on IC 4593, NGC 3918, K 1-2, Wray 17-1, NGC 6337, He 2-186 and K 4-47 – and some of the questions that we try to address.

1. Introduction

The presence of low-ionization structures (LIS) in PNe is poorly understood. They appear as jets, knots, filaments and tails, attached to or detached from the main shell. They are often labeled with specific acronyms trying to describe some of their characteristics – for instance, FLIERs: fast, low-ionization emission regions (Balick et al. 1993); or BRETs: bipolar, rotating, episodic jets (López, Vázquez, & Rodríguez 1995). Despite these pieces of information, the only clear characteristic of all PNe containing LIS is the presence of features much more prominent in low-ionization lines (such as [NII] and [SII]) than in the more highly ionized ones (typically H α and [OIII]).

There exist some families of models trying to explain the origin of the LIS. Basically, these are: interaction stellar wind models (Frank, Balick, & Livio 1996; García-Segura et al. 1999); jet interaction with the circumstellar medium (Cliffe et al. 1995), and the interaction of the shell with the interstellar medium (Soker & Zucker 1997). See Mellema (1996) for a review of LIS and their models. In addition, some ingredients – such as stellar magnetic fields, rotation; precession, a binary system in the center, and dynamical (Kelvin-Helmholtz and Rayleigh-Taylor) and/or radiation in situ instabilities – can be considered in these families of models in order to try to match the observations.

2. Results for two samples of PNe with LIS

2.1. Literature sample

We searched in the literature for PNe which present LIS, finding about 50 objects. From this sample $\sim 50\%$ have jets or jet-like structures and $\sim 35\%$ present any other kind of symmetric LIS (radially symmetrical or point-symmetric pairs). The remaining $\sim 15\%$ are PNe that show LIS more or less oriented in the radial direction, probably being the effect of the ionization front when interacting with density or ionization fluctuations occurring in the circumstellar gas (see, for instance, Soker 1998).

Symmetric LIS should be analyzed deeply, since they certainly gives us clues to their formation processes. In this way, a precise definition of the structures we are talking about is necessary. Hereafter we refer to as “jets” the high-collimated LIS which: are not isolated knots but are extended in the radial direction from the central star; appear in opposite symmetrical pairs; and move with velocities substantially larger than those of the main shell, whose typical velocities are of $20 - 40 \text{ km s}^{-1}$. On the contrary, the features with the morphological appearance of jets, but which move with velocities similar to those of the main shell, or without available kinematical data, are called jet-like structures. It is clear that projection effects, which are often poorly known, play a fundamental role in distinguishing genuine jets and jet-like LIS. Detailed spatio-kinematic modeling of both the main nebulae and the LIS are therefore mandatory.

2.2. Our new data on LIS

We obtained high-quality narrow-band images and long-slit spectra for a sample of PNe: IC 4593 (Corradi et al. 1997); NGC 3918, K 1-2 and Wray 17-1 (Corradi et al. 1999a); NGC 6337, He 2-186 and K 4-47 (Corradi et al. 1999b); IC 2553 and NGC 5882 (Corradi et al., in preparation). In analyzing these data, via spatio-kinematic modeling, our goal is to determine the 3-D geometrical and kinematic parameters which can, in turn, constrain the LIS formation models.

2.3. Jets and jet-like LIS

Our preliminary results, in particular concerning those PNe which present jet or jet-like LIS, are puzzling. We follow the morphological classification of Schwarz et al. (1993) and the similar one of Manchado et al. (1996), and find that most of the PNe with LIS are not spherical: ellipticals ($\sim 23\%$); bipolars and quadrupolars ($\sim 23\%$); point-symmetric ($\sim 27\%$); irregulars ($\sim 20\%$); or spherical ($\sim 7\%$). Thus LIS seen to appear in all morphological classes, but less frequently in the spherical one.

In addition, part of PNe with LIS do not have kinematic data published, which makes a deeper analysis impossible. Others, such as, IC 4593 (Corradi et al. 1997), NGC 7009 (Balick et al. 1998), K 1-2 (Corradi et al. 1999a), He 2-429 (Guerrero et al. 1999), do have kinematic measurements, and their jet-like LIS have very low radial velocities. After deprojection for inclination the expansion velocity of NCG 7009, for instance, would put it in the class of jets (adopting the inclination angle of Reay & Atherton 1985), but there are arguments against the jet-like structure of IC 4593 being close to the plane of sky (Corradi et al.

1997). There are PNe which do contain jets, such as Hb 4 (Hajian et al. 1997), NGC 3918 (Corradi et al. 1999a), K 4-47 and He 2-186 (Corradi et al. 1999b).

What kind of features are expected from the jet formation models? If jets are formed by interacting stellar winds (ISW), in the same process in which the main nebulae are formed, then they should have ages similar to that of the main shell and lie along the symmetric axis (or around it, if they are precessing). The case of NGC 3918 is very interesting, since it does have a two-sided polar jet coeval with the highly axisymmetrical shell (Corradi et al. 1999a). However, the jet is much older than the main shell in other PNe such as NGC 6881 (Guerrero & Manchado 1998).

Our observations for NGC 3918, He 2-186 and K 4-47, reveal that the collimated gas along the jets is generally increasing in velocity. Therefore, it is possible that the linear increase of the gas expansion velocity is an intrinsic characteristic of the collimation process itself. Note that the collimation processes in the case of K 1-2 (with a close binary system in the center) and NGC 3918, for instance, could not be the same. An increase in the expansion velocity is the expected behavior of the jets formed in the models of García-Segura et al. (1999), in which the magnetic field of the central star is responsible for the jet collimation.

2.4. Other symmetrical LIS

Here we include all the features that appear in radially symmetrical pairs with respect to the central star (not only along the major axis, but also along other directions), and those that are point-symmetrics; but not those clearly related to jets. One third of the sample present this kind of symmetry: NGC 6751 (Chu et al. 1991); Cn 1-5, NGC 2553 (Corradi et al. 1996); NGC 3242 (Balick et al. 1998); NGC 5189, NGC 6826 (Phillips & Reay 1983); NGC 6337, Wray 17-1 (Corradi et al. 1999a); and others.

What physical processes could be responsible for these structures? The idea of bullets ejected by the central star is very appealing indeed. However, there are problems with this model, since ballistic motions are clearly difficult to maintain in a hydrodynamical environment. MHD models of García-Segura et al. (1999, and this volume) could apply here too. The latter could explain these symmetrical LIS only if for any reason the jet emission is obscured, except in the jet heads. In fact, this is not an unlikely possibility. New models presented in this meeting – the stagnation knots from partially collimated outflows – appear to reproduce symmetrical LIS, which appear not related to jets, such as the FLIERs of NGC 3242 and NGC 7662 (Balick et al. 1998), and in this model knots are formed in the zone of stagnation of bipolar shells (Steffen & López, this volume).

3. Conclusions

We have briefly discussed some of the very puzzling characteristics of low-ionization structures in PNe. The need for a good determination of the basic parameters and detailed constraints to the LIS formation models is strongly emphasized. In addition, the predictions of current models, when compared to the observations, is far from satisfactory, and detailed modeling of LIS is clearly a

matter that requires urgent attention. To date, the models for the jet formation which best agree with observations are those that consider a stellar magnetic field, even though there is no real evidence for the presence of magnetic fields in post-AGB stars or PNe. What kind of direct or even indirect evidence for these fields one would expect? Finally we would like to raise one more question. Since the majority of the LIS lie in non-spherical PNe, are the processes responsible for the formation of LIS the same processes that are causing the asphericity?

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